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Assessment of anisotropy of extruded tubes by ring hoop tension test

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Abstract

The extraction of mechanical properties of tubes in the hoop direction was accomplished with the ring hoop tension test. In this test, a ring extracted from the tubes is placed over two D-shaped mandrels that are then parted with the aid of a testing machine. A detailed numerical investigation was performed to establish the validity of this test. In particular, the effect of the friction and of the radial through-thickness stresses that are induced due to the contact between the ring and the die was examined in detail. It was discovered that in a well-controlled test, these effects are comparable or lower to testing of a tube by hydraulic inflation which is a reliable method for obtaining the hoop properties of tubes. After the numerical investigation, a series of ring hoop tension tests were performed on Al-6061-T4 tubes. Three-dimensional Digital image correlation (DIC) was used to capture the strain evolution in the gage section of the specimens. By comparing the hoop with the axial response, the material anisotropy of the Al-6061-T4 tubes was established. As a further step, a series of notched ring hoop tension test specimens were designed and tested. By controlling the orientation of the notch, multiple points on the yield surface of the material are obtained.

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1. Introduction

A good assessment of a material's hoop properties is necessary to develop accurate and reliable numerical simulations to properly predict and prevent failure in tube hydroforming (Korkolis & Kyriakides, 2011a, b). The ring hoop tension test originally proposed by Arsene and Bai (1996, 1998) can accurately measure the hoop

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properties of a tube using a universal testing machine. In this test, a dogbone specimen geometry is machined on a ring extracted from the tube and placed over two closely fitting D-shaped mandrels that are parted with the use of a tension testing machine. Since the curvature of the dogbone reduced section of the ring does not change during testing, the specimen undergoes only stretching and no bending resulting in a state of uniaxial tension in this region. The corresponding hoop flow response can be measured easily and when it is compared to the axial flow response the material's anisotropy can be assessed.

2. Ring hoop tension test

2.1. Experimental procedure

The experiments were performed on Al-6061-T4 tubes of 60 mm outside diameter and 3 mm nominal thickness. The tubes were extruded and have a thickness eccentricity of ±4%. A 12.7 mm (0.5") ring is extracted from the tube and a dogbone shape is machined into the ring following the ASTM E-8 standard for a subsize specimen. Two D-shaped mandrels of hardened steel were fitted inside the ring with minimal gap (0.5 mm undersized diameter). Friction between the ring and mandrels was minimized by using layers of Teflon tape and oil. The ring is placed over the mandrels such that the reduced section will remain on the top mandrel during deformation to avoid bending.

2.2. Experimental results

An aspect ratio of gage length divided by thickness (AR=L/t) of 8 is used, allowing for complete development of uniaxial tension in the gage area, as well as maintaining good optical lines of sight for the DIC cameras. The full strain field measured by the 3D DIC from the ring hoop tension test is shown in Fig.1a. In Fig. 1a, the average engineering hoop strain of the gage length, as would be measured by a traditional extensometer, is 14%. Fig. 1a shows a strain gradient along the reduced section that occurs due to the eccentricity of the ring. For the specimen shown in Fig.1a, the cross-sectional area is lowest at the top of the specimen, resulting in the higher strains noticed in that location.

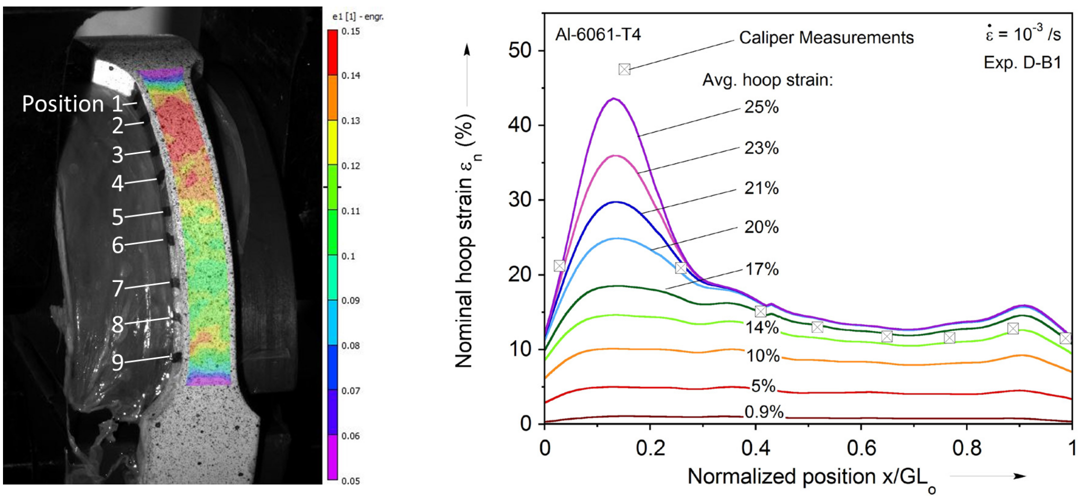

Fig. 1. Ring hoop tension test experiment: (a) DIC hoop strain field on specimen; (b) Specimen hoop strain evolution.

The strain evolution of the ring hoop tension test specimen is shown in Fig. 1b. The engineering hoop strain is plotted along the gage length for increasing average engineering hoop strain, as would be measured by a traditional extensometer. The inset of Fig. 1b is the initial cross-sectional area profile of the gage length. Caliper measurements were taken after the test for comparison to the DIC measurements and also shown in Fig. 1b.

The average engineering hoop stress in the reduced section is calculated by dividing half of the load cell force, output from the testing machine, by the average initial cross-sectional area. The average engineering hoop strain of the gage length is measured by using the DIC virtual extensometer tool. This average stress-strain response is shown in Fig. 2. The local engineering hoop stress strain response (see Fig. 2) can also be calculated for each location (1-9) along the gage length. The local engineering hoop stress is calculated by dividing half the load cell force with the initial local cross-sectional area. The local engineering hoop strain is determined using a miniature virtual extensometer at the each location. Each stress-strain response follows the same flow curve as expected. Elastic unloading is seen in locations 4-8, while locations 2 and 3 localize and experience far more deformation. Fracture occurs at location 2 in this specimen as to be expected based on the initial area profile shown as an inset of Fig.2.

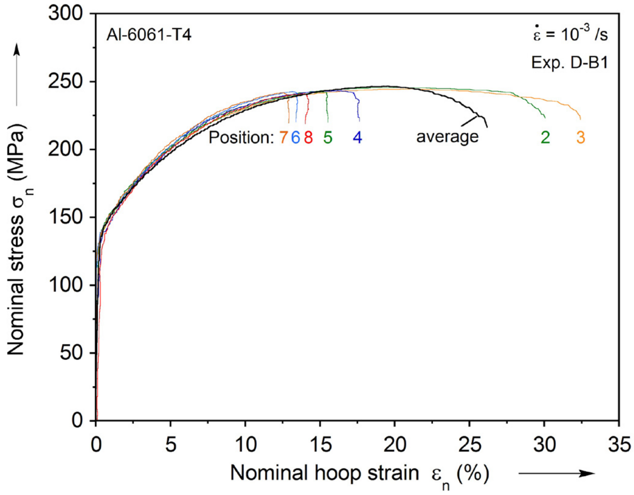

Fig. 2. Local and average engineering stress-strain responses from ring hoop tension test.

2.3. Effects of eccentricity, contact pressure and friction

The tube eccentricity was found to have no effect on the response, for the geometry and material examined here (Dick & Korkolis, submitted). The effect of friction and contact pressure between the ring and mandrel were investigated by use of finite element analysis. The induced compressive stress from the contact pressure at the inside surface of the ring was found to be on the same order as is found in the usual tube inflation experiments used to determine a tubes hoop response (Korkolis & Kyriakides, 2008). This radial stress was determined to not impair the state of uniaxial tension concluding that the contact pressure is negligible in the ring hoop tension test. Friction was determined to play a potentially major role in the ring hoop tension test (Dick & Korkolis, submitted). As the friction increases, the recorded response and actual response become further apart. When the friction coefficient is low, such as 0.01, the effects of friction can be neglected, but for higher values the effects of friction have to be corrected for. The friction coefficient of our experimental setup was calibrated by comparing the variation in strain along the gage length of a ring hoop tension test experiment to that of a simulation with various friction coefficients and was found to be 0.1.

With the known friction coefficient of the system, the effects of friction were corrected for by comparison of FEA to the experimental data. A proposed hoop response of the material was constructed manually, (blue curve, Fig. 3), and used in the FEA of an eccentric ring simulation with the proper friction coefficient. This simulation output response (green curve, Fig.3) was compared to an eccentric ring experimental data (red curve, Fig. 3).

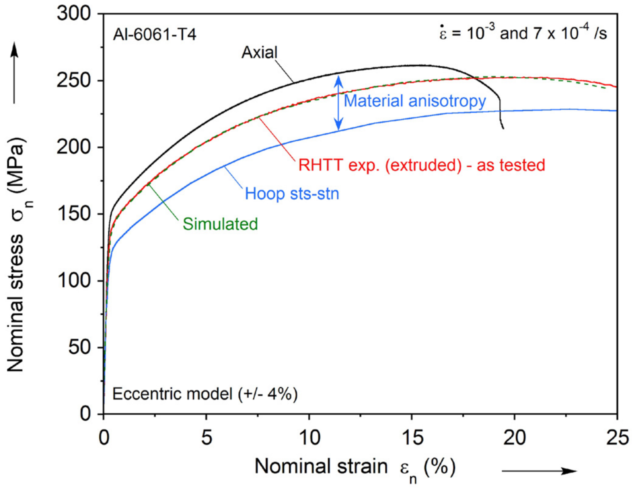

Fig. 3. Material anisotropy, final hoop stress-strain response in blue.

The simulation matches the experimental data therefore the input material (blue curve, Fig. 3) is the hoop response of the material. The axial response of the material was determined in previous work (Dick & Korkolis, submitted) and shown as the black curve in Fig.3. By comparison between the hoop response and axial response in Fig. 3, the material anisotropy can be established.

3. Angled specimens

3.1. Concept

The anisotropy of the tubes was probed by performing ring hoop tension test experiments on specially designed specimens with angled notches. These geometries were designed to induce different loading paths. Fig. 4 shows several specimen geometries that each achieve a plane-strain condition between the notches.

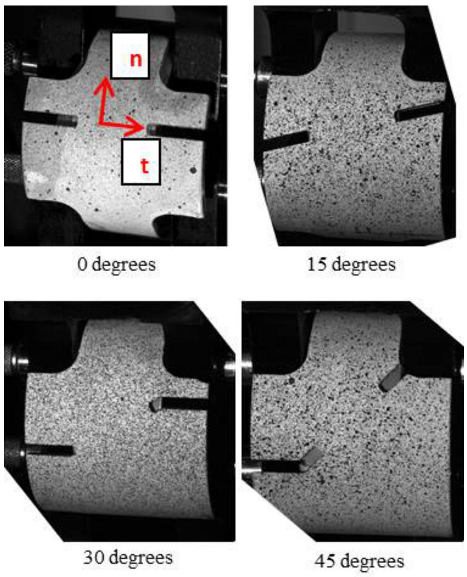

Fig. 4. Plane-strain specimen designs for notches of various angles.

3.1. Testing

Each specimen geometry was tested under the same conditions as was discussed for the ring hoop tension test. The experimental strain results of the zero degree specimen (top left, Fig.4) are shown in Fig. 5. The evolution of the normal and tangential logarithmic strains are plotted as a function of normalized distance across the gage length. It can be seen that the specimen achieves a plane-strain condition in the central region of the gage length.

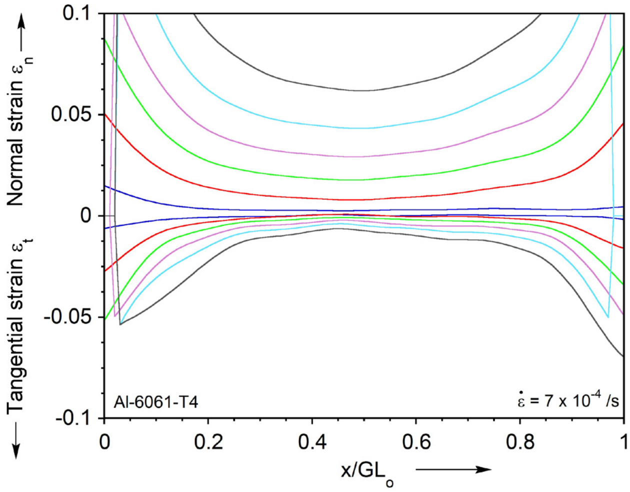

Fig.5. Evolution of the normal and tangential strains ε_n and ε_t.

The normal σ_n and shear τ_{nt} engineering stresses are calculated by decomposing the load cell force measured by the testing machine into normal and tangent components, dividing them by half and then by the initial cross-sectional area between the notches of the specimen. The von Mises assumption for plane-strain is used to determine the normal stress σ_t.

The strain of the specimen is measured using 3D DIC. The area at the center of the gage length between the notches is probed and the extensional ε_n and ε_t and shear ε_{nt} strain components are recorded. If the stress state at this same central location is known equation 1 can be used to determine the plastic work increment at this point in the specimen.

$$dW^p = \sigma_{ij} d\varepsilon^p{}_{ij} \ . \tag{1}$$

The plastic work is found for each specimen using this process. Since the stress fields are non-uniform, finite element models of each geometry are simulated and the normal stress profile across the gage length is recorded. The predicted normal stress (F/A), which is the average stress on the notch is corrected based on these FEA results. The force is also corrected for friction. The corrected stress state is used to calculate the plastic work and compare specimens of different notch angles to each other.

This post-process technique was verified using isotropic FEA to prove that when the data is deduced in this way the resulting stress state data point lies on the material's yield surface. Figure 6 shows this post-process verification for the specimen with the 0^o notch orientation. The data point is from the isotropic FEA results processed as an experiment would be and given the force and stress corrections discussed above. The point is plotted against the yield surface of the material that corresponds to the amount of plastic work chosen for the stress state shown. The point lies on the von Mises yield surface (Fig. 6), verifying the validity of this procedure.

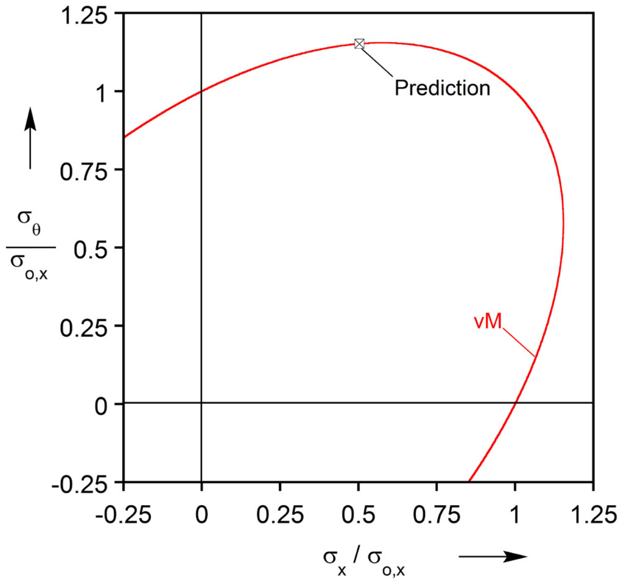

Fig.6. Von Mises yield surface with isotropic FEA stress state prediction.

4. Conclusion

The ring hoop tension test is a simple and reliable method to determine the hoop properties of a tube. The effects of contact pressure and eccentricity were found to be negligible. Friction can be calibrated and corrected for with the assistance of FEA. Plane-strain specimens can be used to determine various stress paths and probe the material's evolving yield surface.

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